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UNCERTAINTIES IN THE ESTIMATES OF SEISMIC GROUND MOTION AT A SITE MADE USING THE SITE SPECIFIC SPECTRA APPROACH

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UNCERTAINTIES IN THE ESTIMATES OF SEISMIC GROUND MOTION AT A SITE MADE USING THE SITE SPECIFIC SPECTRA APPROACH*

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ABSTRACT

This paper describes the site specific spectra (SSSP) approach used by NRC as one of its checks in the safety assessment of nuclear power plants. The SSSP approach is placed in the context of other methods for estimating the ground motion at a site. The sources of uncertainty are categorized and estimates of the contribution to the total uncertainty from each category are made. SSSP are developed for deep soil and rock sites for MM VII and MM VIII SSE levels to cover many of the cases for sites in the eastern United States.

1. INTRODUCTION

It is generally agreed that there is considerable uncertainty in estimates of ground motion at a site from any postulated earthquake. There are a number of sources contributing to the uncertainty which can be lumped into three major categories:

1) Uncertainties due to "source effects", e.g., fault geometry, and the rupture physics, etc. which varies from earthquake to earthquake.

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2) Uncertainties introduced because the travel path from the fault to the site varies from earthquake to earthquake and site to site. We also include the relative geometry of the site relative to fault (radiation pattern effects) in this category.

3) Uncertainties introduced by the local site's geology. Although technically part of the travel path, it is worthwhile to single out the last few hundred meters of travel path. Also lumped into this category are recording building/pad effects.

There are several generic approaches that can be used to estimate the ground motion at any given site from some postulated earthquake:

1) Detailed numerical-theoretical modeling the fault geometry, rupture physics, travel path and site geology.

2) Empirical approach using regression analysis techniques applied to "appropriate" data sets to obtain relations between the expected ground motion and the parameters of the postulated earthquake, e.g., magnitude, distance away, etc.

3) Use of empirical/theoretical models, e.g., the random vibration (Stochastic) approach.

The use of any one of these techniques is plagued by our lack of understanding of the relative significance of each of the three main categories of uncertainties.

In this paper we want to examine, in particular, how these uncertainties impact the estimations made by a specific approach (the SSSP approach) and, in general, attempt to shed some light on the relative importance of each of the main sources of uncertainty.

2. SITE SPECIFIC SPECTRA APPROACH

The SSSP approach was suggested by Bernreuter (1979). It is a variation on the "regression analysis" approach. Typically, the regression analysis approach attempts to fit a model of the form:

$$\log y = C_1 + C_2M + C_3\log\,(\text{distance metric}) + C_5\,(\text{distance metric}) + C_6\,(\text{site type parameter}) + E \qquad (2.1)$$

where: y = ground motion parameter of interest, e.g., peak acceleration, spectra acceleration at some frequencies, etc.
C_i = constants to be determined from the analysis.
E = error term, with zero mean and standard deviation σ

to some appropriate data set. If indeed one had a large unbiased data set, then the problem would be simple. But, we do not have such a data set, although for some areas it is improving rapidly. Unfortunately, nuclear facilities are located in the eastern United States (EUS) where the data set is very limited.

The SSSP approach was developed as an attempt to overcome the lack of data in the EUS. The assumption is made that, on the average, major differences between the ground motion observed from typical EUS earthquakes and the ground motion from earthquakes of the same "magnitude" recorded elsewhere are primarily due to attenuation (travel path) and local site effects differences. The travel path differences can be minimized by use of a suite of records of the appropriate magnitude range recorded "near" the epicenter or rupture surface. The local effects can be minimized by the use of records recorded on similar site conditions. The estimated SSSP is obtained by averaging all of the response spectra computed from the selected suite of ground motion recordings. In most applications of the SSSP approach it has been assumed that the distribution of spectral amplitudes at any period is lognormally distributed. This assumption is also made in this paper. Generally, the 1-sigma spectrum resulting from the averaging process is used. Under the lognormal assumption it becomes the 84th percentile spectrum.

In selecting the suite of records a number of questions arise:

- What is the appropriate magnitude range to use?
- What is the appropriate distance range to use?
- What distribution on distance is appropriate?
- How many earthquakes/travel paths must be in the data set?
- How "similar" must the recording sites be to the site at which the prediction is to be made?

The answers to some of these questions are, of course, regulatory issues, e.g., what earthquake is the selected suite of earthquakes attempting to model? In all cases, the answers depend on our understanding of the relative contribution to the uncertainty from the three major categories of sources of uncertainty. For example, if all earthquakes of the same magnitude M had basically the same source properties, then one would only need a few earthquakes to capture the potential variation in ground motion observed at a site from earthquakes of magnitude M.

The U.S. Nuclear Regulatory Commission (NRC) practice, Kimball (1983), Reiter and Jackson (1983), has been to utilize acceleration histories from a suite of earthquakes whose magnitudes are within $\pm$ 0.5 magnitude units of the target. For EUS sites, the safe-shutdown-earthquake (SSE) is defined in terms of Modified Mercalli (MM) epicentral intensity, in most cases either MM VII or MM VIII. NRC has generally assumed that a M_L = 5.3 earthquake models a MM VII and a M_L = 5.8 models a MM VIII earthquake.

In terms of the target distance, NRC has generally utilized acceleration time histories recorded within 25 km of the source with the average distance being 15 km. No clear criteria have been developed to define "similar" site conditions. Generally, there is little data which can be used to define the site conditions at most accelerograph sites. This lack of data makes it difficult to select records recorded at sites with "similar" site conditions. Thus one of the major objectives of this study is to attempt to determine a measure of what "similar" might entail.

3. MODEL FOR THE UNCERTAINTY

A typical example of the uncertainty resulting from a typical application of the site specific spectra approach is illustrated on Fig. 3.1a which shows an overplot of all of the spectra selected to define the site specific spectra for a deep soil site in the EUS. For this case, the SSE was specified as MM VII. As noted in Section 2 it is assumed that the spectral values at any period are lognormally distributed. Figure 3.1b shows the resultant median and 84th percentile spectra for the set of spectra shown on Fig. 3.1a. The uncertainty, under the assumption of the lognormal distribution, is measured by the size of σ_T, the standard deviation of the assumed lognormal distribution. It is seen from Figs. 3.1a, b that the uncertainty is considerable. Considering the large uncertainty in the SSSP estimate for the SSE at a typical deep soil site in the EUS, one might ask if the large uncertainty is due primarily to factors which are indeed uncertain such as: the rupture process of the earthquake; it's possible location relative to the site; it's magnitude; or if the large uncertainty is primarily due to the fact that data recorded at a too diverse set of sites was used.

To address this question we need to better understand the relative contribution of each of the categories to the uncertainty defined in Section 1.

To the first order, we can model σ_T by the relation:

$$\sigma_T^2 = \sigma_S^2 + \sigma_{TP}^2 + \sigma_{LS}^2 + \sigma_M^2 + \sigma_R^2$$

where σ_S = Contribution to the uncertainty in the observed spectra due to variations in source parameters between earthquakes of the same magnitude.

σ_{TP} = Contribution to the uncertainty in the observed spectra due to travel path and seismic radiation pattern variations.

σ_{LS} = Contribution to the uncertainty in the observed spectra due to the fact that the records were recorded at different sites and in different buildings.

σ_M = Contribution to the uncertainty in the observed spectra because a range of magnitudes was used.

σ_R = contribution to the uncertainty because a range of distances (geometric spreading) was used.

In the application of a typical regression analysis approach, one is generally interested in σ_S, σ_{TP} and σ_{LS}, as explicit terms are included to account for neglecting the fact that earthquakes of various magnitudes and distances are used. However, in the site specific spectra approach, σ_M and σ_R could be significant.

Unfortunately, it is very difficult to study the relative contribution of each of the component σ's to σ_T. Ideally, one would like to isolate each factor, e.g., fix the site and travel path and examine the recorded ground motions from a wide variety of earthquakes. Clearly, this is not possible. The best that can be expected is a series of nearby earthquakes. To study travel path, one would like to fix the source and site and vary the location of the earthquakes. If all earthquakes were truly similar then this would be possible, but this is clearly not the case. If one knows σ and σ_{TP}, then one could estimate σ_{LS} by using data at fixed sites at which a number of earthquakes have been recorded and data at various sites recorded for the same earthquake. These questions have been addressed to some extent by Bernreuter (1979), McCann and Boore (1983) and McCann (1983). McCann (1983) and McCann and Boore (1983) used data from the 1971 San Fernanco earthquake recorded at several nearby subsets of locations to study σ_{TP} and σ_{LS}. It is difficult to draw firm conclusions because only one earthquake is involved and unfortunately a wide variety of buildings/depths of instrumentation are involved, although the building type and depth of the recording instrument were explicitly accounted for.

4.0 UNCERTAINTY INTRODUCED BY THE TRAVEL PATH

Because of the difficulty of fixing the travel path, it is worthwhile to first examine how much variation in the observed ground motion at a fixed site from a source with fixed parameters is introduced by changes in the travel path. Because this variation can be considerable (as will be shown in the next section), the data we propose to use to address this issue consists of the ground motion recorded from large underground nuclear explosions (UNE).

Figure 4.1 shows the 5 percent damped relative velocity spectra obtained from data recorded from 5 UNE at the Nevada Test Site (NTS). These 5 events each had a yield $\pm$ 4 kilotons of each other and the distance between the UNE and the recording station (station 10) was 55 $\pm$ 2 km. All of these UNE were located in Pahute Mesa area of NTS within a few kilometers of each other. It is observed from Fig. 4.1 that there is considerable variation between the spectra from event to event.

Figure 4.2 shows the envelope, median and 1-Sigma spectra based on the spectra for the five UNE shown in Fig. 4.1. As noted in Section 3 the computation is made assuming that the distribution is lognormal. The uncertainty as measured by standard deviation of the natural log of

S_v (σ_{LnSv}) varies the with the period with an average value of about 0.2. It is observed that there is as much as a factor of two difference between the computed median and the maximum observed value. It should be noted that if only the radial component is used the spread is somewhat reduced to a factor of 1.6. These results indicate that very minor variations in the travel path can induce considerable uncertainty in the observed ground motion at a site. There is some additional data, discussed in Section 6, which sheds additional light on the question of just how much variation in the observed ground motion at a site is due to only variations in travel path.

5.0 UNCERTAINTY INTRODUCED BY THE SOURCE

The question we would like to address in this section is: assuming that one could fix the site and travel path, what is the uncertainty in the observed ground motion at a fixed site from all possible earthquake source mechanisms for earthquakes of magnitude M? Note that this uncertainty could well be a function of M with it being larger for large earthquakes as compared to smaller earthquakes. There is very little data to address this issue. Thus, it is useful to first examine simple theoretical models to see what help they can give us, and use the little available data to see how well the simple theoretical models match reality.

Typically, to the first order, Brunes' model (1970) is used to represent the source spectrum of an earthquake. Brunes' model relates a few fundamental parameters of the earthquake to the Fourier amplitude spectrum of the displacement. The source function that would be observed at a distance R from the source in a half-space, (i.e., no complexity of layering transmission path, etc.) is:

$$FS_d(R,\omega) = \frac{K\Delta\sigma}{Rf_o} \frac{1}{\omega^2 + f_o^2} \tag{5.1}$$

where

$\Delta\sigma$ = Stress drop (source parameter)

f_o = Corner frequency (related to the rupture area)

R = Distance

K = constant

Using this simple model and a few other assumptions, Thatcher and Hanks (1973) showed that the local magnitude M_L of an earthquake is related to the parameters of Brunes' model of an earthquake by the relation

$$M_L = \log\Delta\sigma - 3/2 \log f_o + C \tag{5.2}$$

Thatcher and Hanks (1977) showed that this relation fits the data. Using Eqs. (5.1) and (5.2), it is relatively easy to show that

$$FS_a(R,\omega) = \frac{K f_o^{1/2}\, 10^{M_L}}{R} \quad \frac{\omega^2}{\omega^2 + f_o^2} \tag{5.3}$$

where FS_a = Fourier spectrum of the acceleration

There is a close relationship between FS_a and the undamped relative velocity spectrum of interest in structural analysis. Eq. (5.3) shows that for a given magnitude we can expect the level of FS_a to vary as $\sqrt{f_o}$. Thatcher and Hanks (1973) provide measured data which suggest that f_o varies by about an order of magnitude for earthquakes in the range of 4.5 to 6.5. Thus, we would expect at a minimum up to a factor of 3 difference between the maximum and minimum levels of FS_a. If one thinks in terms of the SSSP approach, all of these earthquakes would be averaged together relative to the median prediction, we might expect that our uncertainty as measured by Sigma ($LnFS_a$) would be in the range of 0.4 - 0.5 or a factor of 1.5 or so uncertainty.

Figure 5.1 shows the 5 percent damped relative velocity spectra (both horizontal components) for two earthquakes of approximately the same magnitude

($M_L = 4.6$) and within a few kilometers of each other, computed from records obtained at the Oroville Airport. It is observed that the relative level of the high frequency (short period) spectral amplitudes differ by about a factor of 3. Figure 5.2 shows a similar comparison for two $M_L = 3.6$ earthquakes based on records obtained at the Brawley airport. Although the two earthquakes recorded at Brawley were relatively close together, they are so close to the recording station that the radiation pattern could be a factor in the observed differences between the spectra. Once again the variation between the two earthquakes is about a factor of 3 or more.

Naturally, as the earthquakes become larger, a larger number of "barriers" become involved. Thus, we might well expect to see a wider variation in the observed ground motion at a fixed site.

6.0 UNCERTAINTY INTRODUCED BY THE SITE

In this section we want to examine how much uncertainty is introduced into our ground motion estimates from mixing data recorded at a number of different sites. If the site is fixed, i.e., if we only look at data for a fixed site, then $\sigma_{LS} = 0$, and

$$(\sigma_T)_{\text{fixed site}} = \sigma_S^2 + \sigma_{TP}^2 + (\sigma_M^2 + \sigma_R^2) \qquad (6.1)$$

We can also estimate σ_{LS} from

$$\sigma_{LS}^2 = \sigma_T^2 - (\sigma_T^2)_{\text{fixed site}} \qquad (6.2)$$

To do this, one needs to have recorded ground motion data at a number of sites that have experienced repeated earthquakes. The problem is that there are only a few sites which have ground motion data from a number of earthquakes. Some data sets from UNE also exist which can be very useful as travel path and source effects can be limited. Then, smaller data sets can be used to estimate the reduction in uncertainty achieved by fixing the site relative to a fixed source and travel path.

In addition to the reduction in the uncertainty in our predictions (at a fixed site), we would expect that the median prediction might increase or decrease depending on the actual conditions at any given site. Finally, we might expect the predicted spectrum to have more "character", i.e., have local maximums and minimums relative to a general data set.

As noted, ground motion recorded from UNE can shed considerable light on this question. Lynch (1971) used data recorded at thirteen stations from fourteen UNE to study this problem. Source and travel path variations for each site were minimized by restricting the data to only UNE located on Pahute Mesa. The level of ground motion was low so that the nonlinear effects in the soil at the sites should be small. The sites were located from 52 to 170 km from Pahute Mesa. Lynch (1971) analyzed this data using a covariance analysis that explicitly included each site rather than a typical regression analysis. Briefly, covariance analysis relates a component of spectrum SV at period i recorded at K stations to the yield of events detonated in a restricted area. The statistical model has the form

$$SV_{ik} = A_{ik}W^{Bi} \qquad \begin{cases} i = 1, 2, \ldots, \text{No. of Periods} \\ k = 1, 2, \ldots, K \end{cases} \qquad (6.3)$$

Covariance analysis determines for each component at each period, i, a yield scaling exponent B_i, the standard deviation of the estimate σ_i, and K sets of amplitude coefficients A_{ik}. The amplitude coefficients A_{ik} implicitly reflect the average distance from the event area to the recording station, local station amplification and any factors associated with the transmission path. The parameter σ_i reflects variance due to neglected source parameters, transmission path factors for each station and differential changes in the average distance to each recording station.

A plot of the $\exp(\sigma_i)$ obtained from Eq. (6.3) using the restricted Pahute Mesa data set and the $\exp(\sigma_i)$ obtained from a general regression, Lynch (1969), of the form

$$SV = AW^{B_1}R^{B_2} \tag{6.4}$$

is shown in Fig. 6.1. Figure 6.1 shows that there is a considerable reduction in the uncertainty if the data is restricted to a fixed site.

The data set used by Lynch (1969) was somewhat different than the data set used by Lynch (1971); however, in both cases, the data was restricted to Pahute Mesa UNE. Thus, the reduction in uncertainty can be primarily attributed to fixing the site conditions as source and travel path variations are about the same. It is very interesting to note from Fig. 6.1 that the uncertainty associated with the model described by equation 6.4 is much larger than generally associated with typical earthquake data sets. This is surprising because we have what appears to be a rather homogenous data set compared to typical earthquake data sets. However, a closer look at the make up of the stations involved indicates that a relatively large percentage of them are made up of near-by pairs exhibiting wide variations in response (as illustrated in Fig. 6.2 for one pair of stations, one station being located on a rock outcrop and one located on a nearby soil deposit.)

Lynch and Williams (1972) performed a covariance analysis on data obtained from 22 UNE located at Yucca Flat. Figure 6.3 compares the computed $\exp(\sigma_i)$ of the Yucca Flat data set to the $\exp(\sigma_i)$ of the Pahute Mesa data set. It is seen that they are very similar.

The values of the $\exp(\sigma_i)$ shown in Fig. 6.3 primarily measure the uncertainty introduced by modest changes in travel path as source and site effects have been held constant. From Fig. 6.3 it is seen that σ_i varies as a function of the period but is approximately constant at a value of 0.4. This value of $\sigma_i \approx 0.4$ is larger than the value of σ_{LnSv} observed in Section 4.

This is not surprising because the variations in the travel paths of the data used in Section 4 were smaller than the variations in the travel paths for the data used by Lynch.

Note, however, that both data sets represent rather limited variations in travel paths. Thus for earthquakes we could expect that the uncertainty introduced by travel path alone could be much larger. In addition, the increase in the uncertainty introduced by the radiation patterns of the earthquakes could also be very significant.

If a given site has experienced a number of earthquakes for which records of the ground motion are available, then it is possible to determine if the site generally amplifies ground motion relative to typical correlations such as those developed by McGuire (1978) and Joyner and Boore (1981). It is also possible to determine if the data at a given site are less dispersed than the more general data set for a number of sites. The difficulty is to assess the role that site response factors play relative to source and travel path factors. Source and travel path variations are extremely important. It is difficult to account directly for these factors other than by the simple approach of grouping the available data so that these factors are minimized.

The El Centro and Ferndale sites have the most complete data sets. Both of these sites are deep soil sites, although the overall soil depth is greater at El Centro than at Ferndale, where the soil is somewhat stiffer than at the El Centro site.

Bernreuter (1979) used the data recorded at these two sites to compare the peak acceleration to the mean predicted by typical correlations among peak accelerations, site type, earthquake magnitude, and distance. For his comparison, he used the correlation developed by McGuire (1978) as representative. For soil sites, McGuire determined that

$$a = \frac{24.5 \exp\left[0.89M\right]}{R^{1.17}} \; ; \; \sigma_{1na} = .62 \,, \qquad (6.5)$$

where

M = Local Richter magnitude

R = Distance from energy release

σ = Standard deviation

Figure 6.4 shows a comparison of the recorded acceleration at the El Centro and Ferndale sites normalized by exp 0.89M as a function of R. Also shown, is the median normalized line given by Equation 6.5 and the $\pm$ one-sigma lines. It is evident from this figure that consistently higher-than-average peak accelerations are recorded at the Ferndale site during the earthquakes. The El Centro site appears to have average acceleration.

In order to quantify the dispersion of the data, separate regression analyses were performed for the data at the El Centro and Ferndale sites. The results of these analyses are:

$$\ln(a) = 4.82 + 0.52M - 0.83 \ln(r)$$

$$\sigma_{\ln a} = 0.39$$

for Ferndale, and

$$\ln(a) = 4.12 + 0.53 - 0.85 \ln(r)$$

$$\sigma_{\ln a} = 0.67$$

for El Centro.

There is significantly less scatter to the data at the Ferndale site than to the data at the El Centro site. The data at El Centro have about the same standard deviation as the more general data set used by McGuire, which included eight El Centro records and nine Ferndale records. Although the distances R for the Ferndale events are less certain than for El Centro events, no systematic error appears to exist, and it is unlikely that the errors are large enough to significantly change the conclusion reached above.

We also examined the Oroville data set. We performed regression analysis on the data in Seekins and Hanks (1978) and used the resulting relation to normalize the recorded peak accelerations. Figure 6.5 shows the ratio between the measured and estimated peak acceleration as a function of distance. In Fig. 6.5, the ratios for the Johnson Ranch data are denoted by the symbol J and for the ratios for the Oroville Airport data by the symbol A. The $\pm$ 1-sigma limits are also shown. It is seen that the observed peak acceleration recorded at the Johnson Ranch site is consistently high (6 out of 8 data points above the +1- sigma limit) and the observed peak acceleration recorded at the Oroville Airport is consistently low (9 out of 11 data points below the median. However, there is a much greater spread to the airport data than to the ranch data.

We also examined how the error term might be reduced by going from the general data set to a fixed site. We only examined (for the fixed site cases) those sites at which eight or more earthquakes were recorded. We obtained

$\sigma_{\ln a}$ = 0.60 General data set
0.42 Johnson Ranch Station
0.26 Station 5
0.61 Station 1
0.36 EBH Station

These results are in reasonable agreement with the results for the Ferndale, and El Centro data. There is considerable scatter to the data making it difficult to estimate σ_{Ls} . The "stiffer sites" (Ferndale, Johnson Ranch, Station 5, EBH) show lower $\sigma_{\ell na}$ value than deep than softer stations (El Centro and Station 1).

To estimate σ_{Ls} we need σ_T for fixed sites. We approximated this by defining a site category for each site for the Oroville data set and used the model

$$\ln a = C_1 + \Sigma\, CS_i\, S_i + C_2 M + C_3 \ln R \tag{6.6}$$

where

C_i and CS_i are constants to be determined by a regression analysis

S_i are site categories, S_i is one if the data point was obtained at site i and is zero otherwise

R = hypocentral distance

M = local magnitude

Our fit to the data resulted in a $\sigma_T = 0.52$ for "fixed sites". Using $\sigma_T = 0.60$ from our general fit to the data without site categories we estimate that

$$\sigma_{LS}^2 = \sigma_T^2 - (\sigma_T)^2_{\text{(fixed site)}} = (.60)^2 - (.52)^2$$

$$\sigma_{LS} \sim 0.30$$

McCann and Boore (1983) and McCann (1983) attempted to sort out the various contributions to the uncertainty in the prediction of ground motions using data from the San Fernando Earthquake. McCann (1983) concluded that local site effects contributes about 30% of the uncertainty, i.e. $(\sigma_{\ln a})_{LS} \sim 0.23$ based on a few sites. This result is consistent with our results.

7. UNCERTAINTIES INTRODUCED BY THE RANGE FOR M AND R USED

In a typical regression analysis approach both the magnitude and distance variations are explicitly accounted for. This is not the case in SSSP approach where a range of distances and magnitude are included. Infact it should be noted, that one of the important features of the SSSP approach is to include the potential uncertainties in magnitude and location of the SSE in the predicted spectrum. However, if the uncertainty introduced by the range for M and R are much larger than the uncertainties introduced by the other source of uncertainty, then it would seem necessary to rethink the ranges for M and R used. Recall from Section 2 that the "target" is typically and earthquake of $M_L = 5.3$ (for MM VII SSE) and $M_L = 5.8$ (for MM VIII SSE) with an average distance of 15 km.

A simple estimate of the uncertainty introduced in our estimate of the ground motion using the SSSP approach can be obtained by using the results of typical regression analysis of data sets. e.g., Joyner and Boore (1981) found that

$$\log_{10} a = C_1 + 0.25M - \log_{10} r - 0.0026r$$

$$\text{where } r^2 = d^2 + 53$$

The term -.0026r is relatively unimportant for the distance range out to 25 km. Thus the potential multiplicative error, E^* in the actual value of the acceleration at high frequency end of the estimated spectra obtained by use of the SSSP approach for distances (d) of 0 to 25 km with an average distance of 15 km is of the order

$$0.64 < E^* < 2.3$$

That is, the spectra from the most distant earthquake used will be about a factor of 0.6 smaller than the "target" and the very near fault data might be a factor of 2 larger than the target. These variations are of the same order or on the average smaller as the uncertainties introduced by the other sources of uncertainty.

The maximum potential uncertainty introduced by the range in magnitudes used (± 0.5 units) is on the order of $10^{(.125)}$ or a factor of 1.3. Clearly the actual uncertainty introduced by the distribution of earthquake magnitudes used is smaller and less than the other uncertainties.

8. APPLICATION OF SSSP APPROACH

In Sections 4-7 we attempted to estimate the contribution to the overall uncertainty from each of the three major categories of the sources of uncertainty defined in Section 1. It can be concluded from the results presented in Section 4-7 that each of the three categories defined in Section 1 introduces significant uncertainty into our estimates of the ground motion. We now want to examine what the implication of Section 4-7 are in the application of the SSSP approach.

No single category appeared to contribute more to the uncertainty than any other. However, in the application of the SSSP approach the local site's geology must be treated differently than the other categories because the estimate is for a fixed site and hence, unlike the other parameters, the local geology is not a random variable. Thus we have two conflicting problems in the selection of data. First, because of the fixed nature of the site, we would like to limit our data selection to very similar site conditions. However, our results also show that we can expect large variations in the observed ground motion at any fixed site because of the uncertainties introduced by source travel path effects. This means that we need a large sample to be sure that we have adequately defined the estimated median and 84th percentile spectra. In general, such a sample can only be obtained by relaxing the criteria used to determine if a site is "similar" to the target site because at many accelerograph sites we only have very limited information about the parameters needed to determine if the accelerograph site matches the site for which the prediction is to be made. In fact, when trying to develop SSSP for specific sites one has problems in selecting a suite of appropriate records if the site is other than "deep" soil or weathered rock.

In Fig. 8.1a we compare the SSSP for a deep soil site to that for a weathered rock site for a SSE level of MM.VII and in Fig. 8.1b for a SSE level of MM VII. The major difference between the weathered rock case and the deep soil case is at periods longer than 0.2 seconds where the deep soil SSSP is higher than the rock SSSP. Interesting enough, it does not appear to be much difference between the deep soil and weathered rock SSSP at short periods. Some care was taken in the selection of the records to insure that the soil records were all obtained on relatively deep (deeper than 200 ft) soil. The rock records have a range of rock types, but mostly soft weathered rock.

Figure 8.2, shows σ_T for the rock and deep SSSP plotted in Fig. 8.1a. Because of the large uncertainties in estimated SSSP, it is of some interest to see if the range of sites used had a significant impact on σ_T. One way to get a handle on this is to develop SSSP using data from only one site. Figure 8.3 shows σ_T for a SSSP suite for the Oroville Airport based on six earthquake all with $M_L = 4.7 \pm 0.5$ at an average distance of 13 km. The value of σ_T is very similar to that shown in Fig. 8.2 suggesting that the variation in sites used to develop the SSSP shown in Fig.s 8a and b has not significantly increased σ_T over the contribution for source and travel path uncertainities.

There can be considerable departure from the relatively smooth spectral shape obtained for deep soil and weathered rock sites as is illustrated in Fig. 8.4 where we plot SSSP for the Oroville Airport (deep soil) and the Johnson Ranch (shallow soil). The median SSSP for the airport and Johnson Ranch were developed using only data recorded at the respective sites. Only two earthquakes were common to both data sets, thus the average magnitude and distance of the two SSSP are different. For the Oroville Airport the average M is 4.7 and the average R is 13 km. For Johnson Ranch the average M is 4.4 and the average R is 12 km. The data shown in Fig. 8.4 suggests that there is considerable amplification of the ground motion acceleration at Johnson Ranch relative to the Oroville Airport. This is in general agreement with Fig. 6.5.

An analysis using simple one-dimensional soil column type models e.g., Bernreuter et al. (1986), shows that sites with soil depths less than 200 ft tend to amplify the ground motion as compared to weathered rock or deep soil sites. The analysis also shows that this amplification should be observed even if data from a suite of sites are used, although the uncertainty will be significant. The computed amplification varies with period with a maximum median amplification factor of approximately two relative to a rock or deep soil base case. This indicates that, until more data becomes available at shallower soil sites so appropriate SSSP suites can be formed, considerable care should be taken in the extrapolation of any data set to yield an estimate of the ground motion at such sites.

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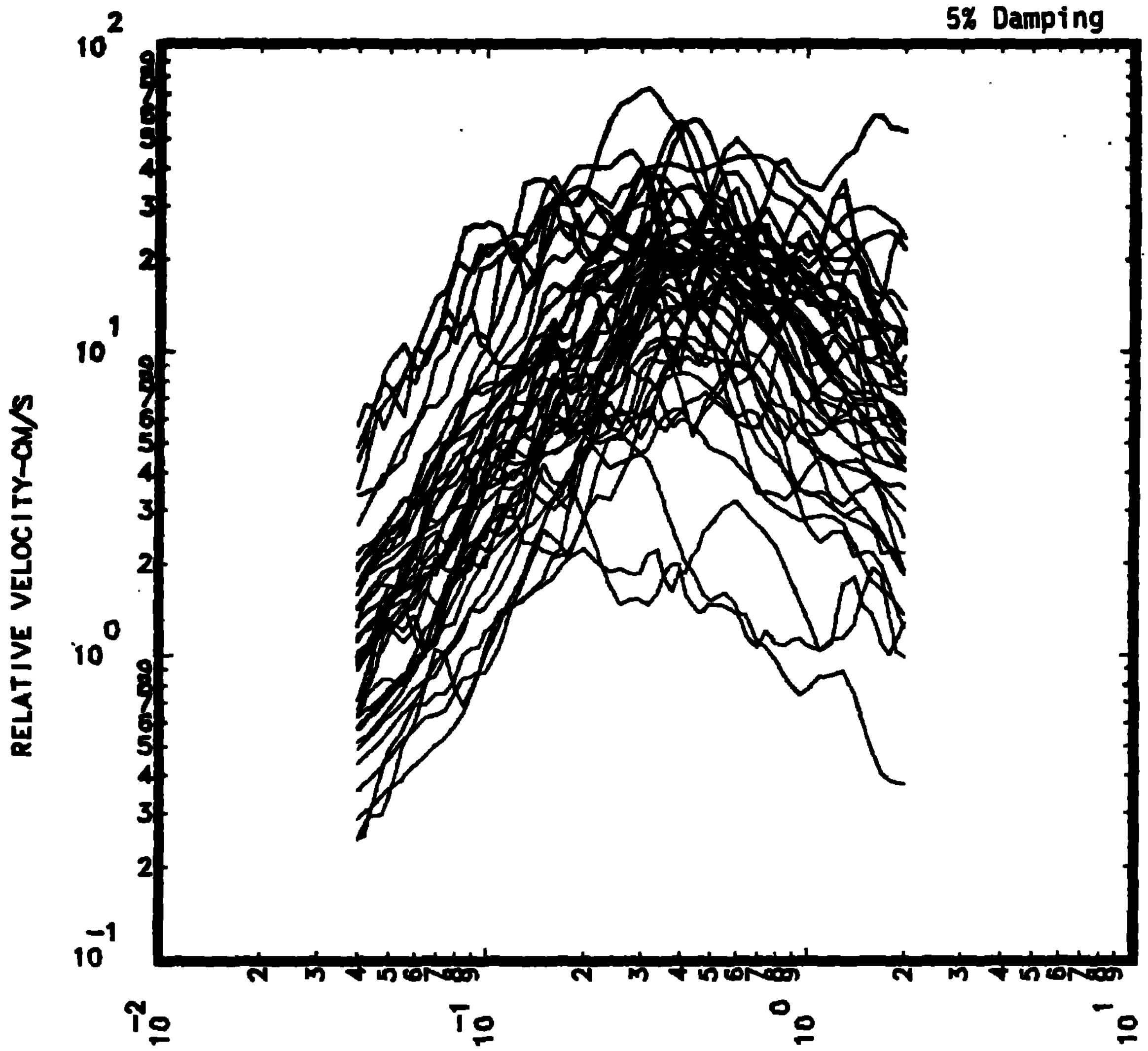

Fig. 3.1.a. Over plot of all of the suite of spectra selected to define the SSSP for a deep soil site having a SSE of MMVII.

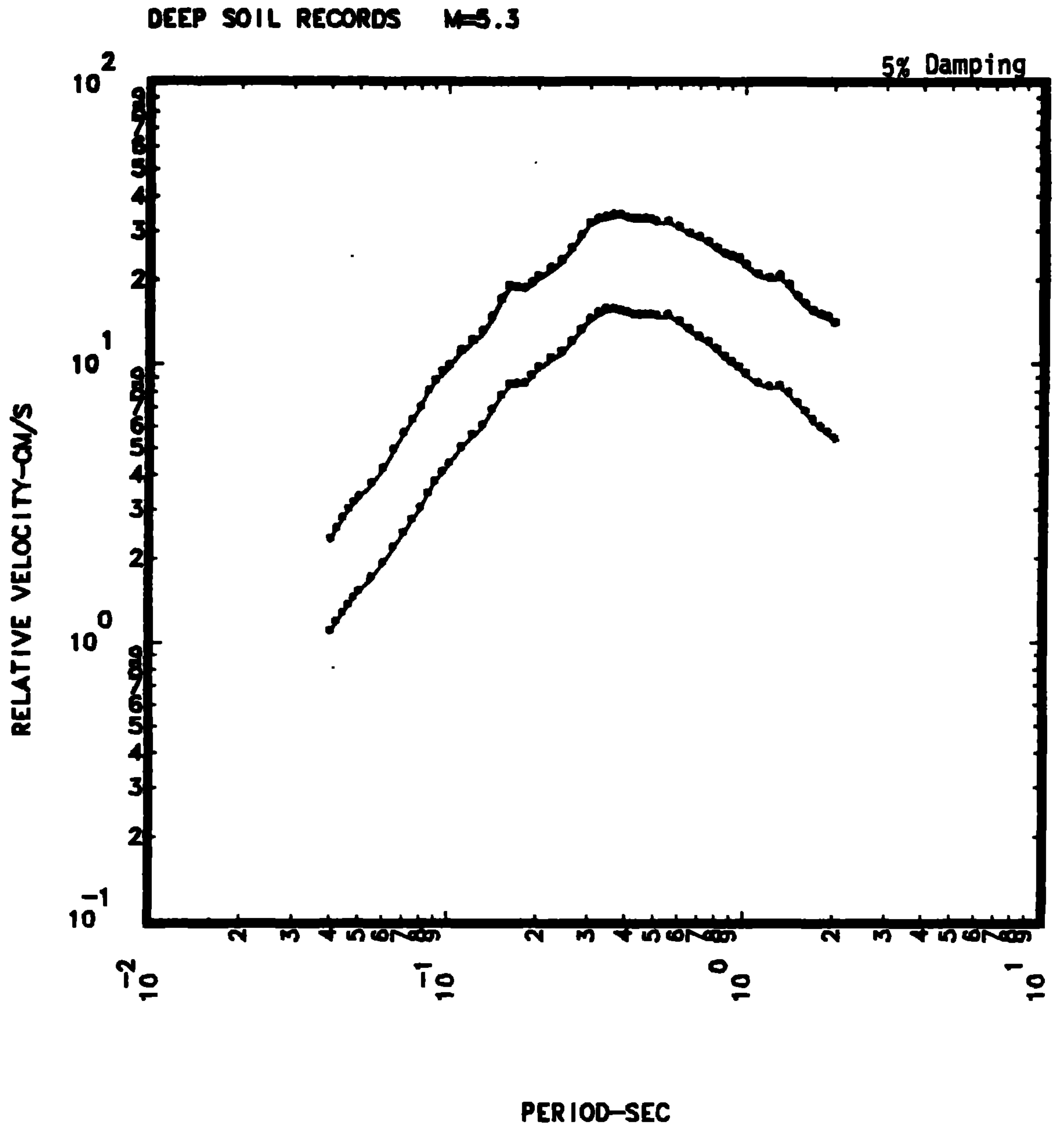

Fig. 3.1b. The Median and 84th percentile spectra of the suite of records shown in Fig. 3.1a.

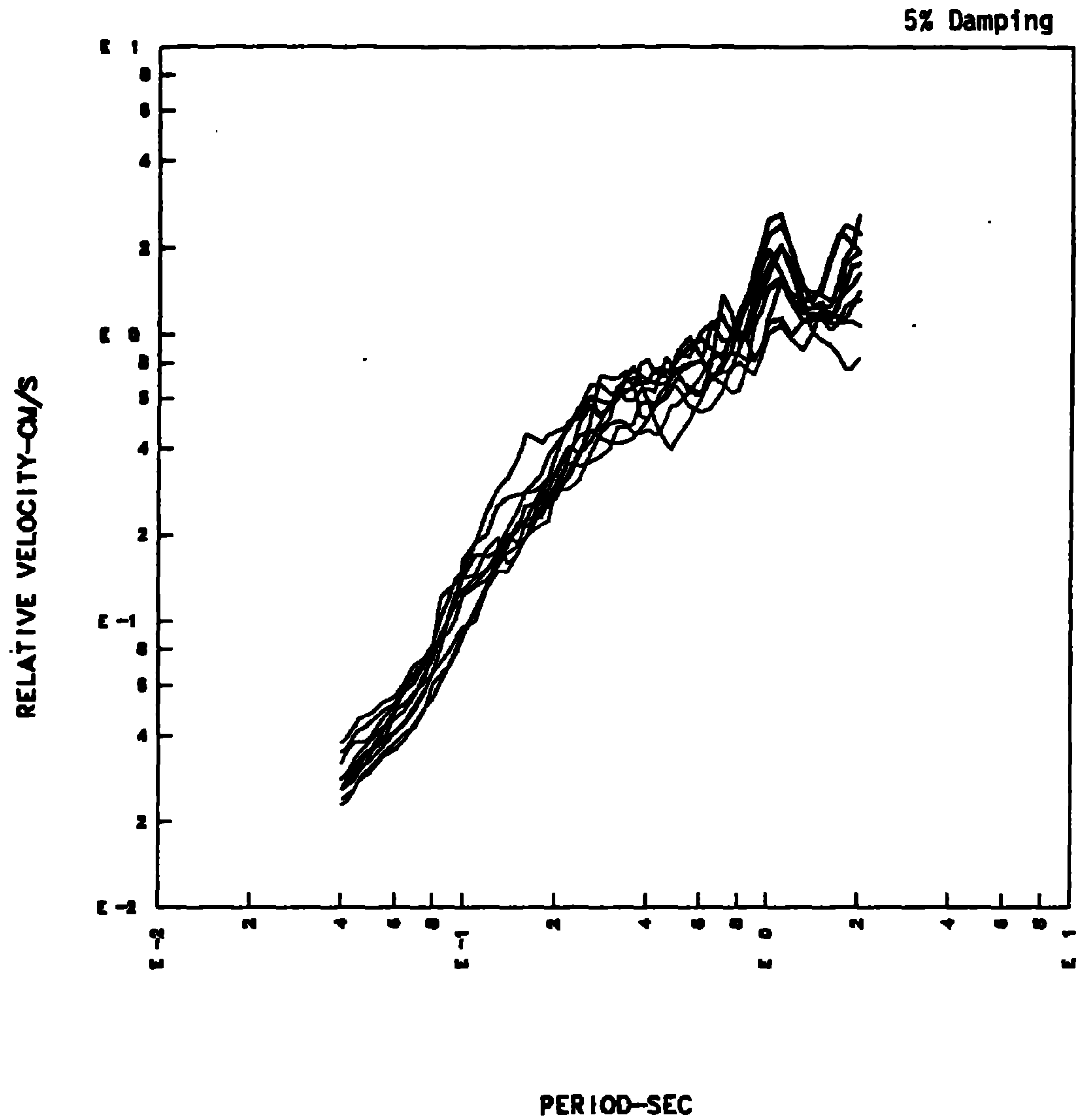

Fig. 4.1. Over plot of both radial and tangential components of 5 UNE recorded at a single deep soil station. These 5 UNE all had a yield of ±5 kilotons of each other at a distance of 55 ± 2 km from the recording station.

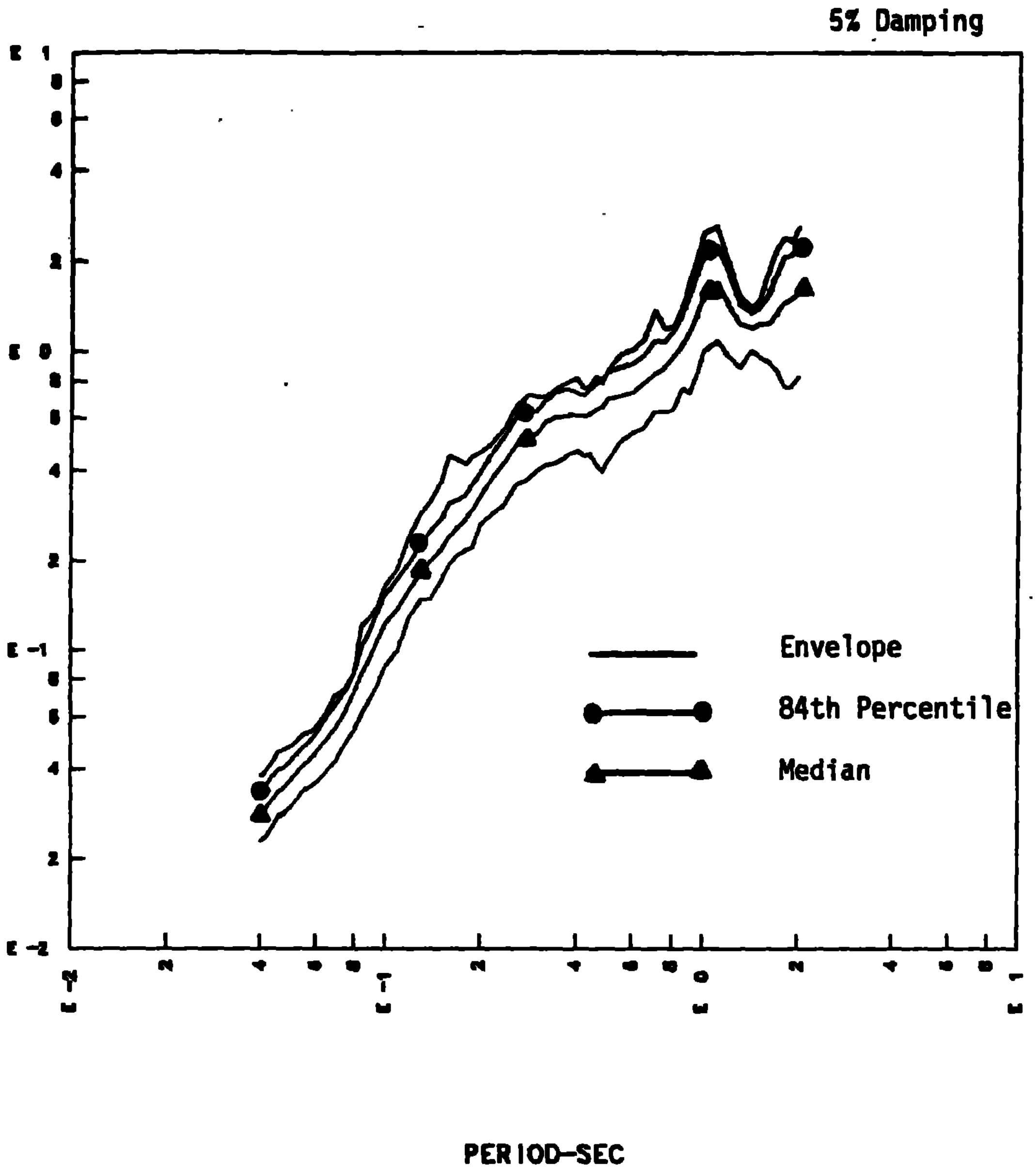

Fig. 4.2. The envelope, median and 84th percentile spectra of the suite of spectra shown in Fig. 4.1.

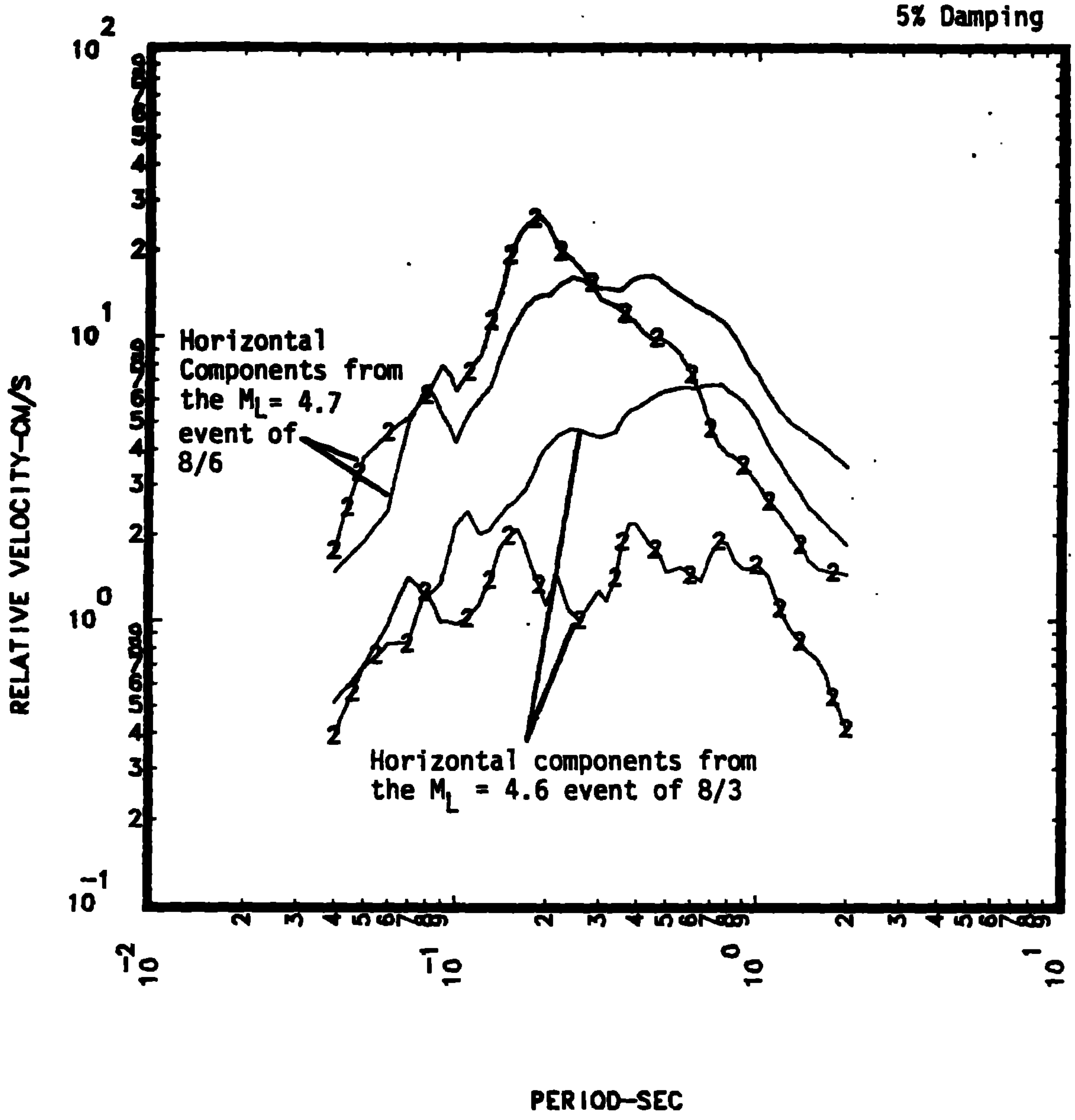

Fig. 5.1 Comparison of the spectra from two earthquakes located within a few kilometers of each other with similar M_L and recorded at the Oroville Airport.

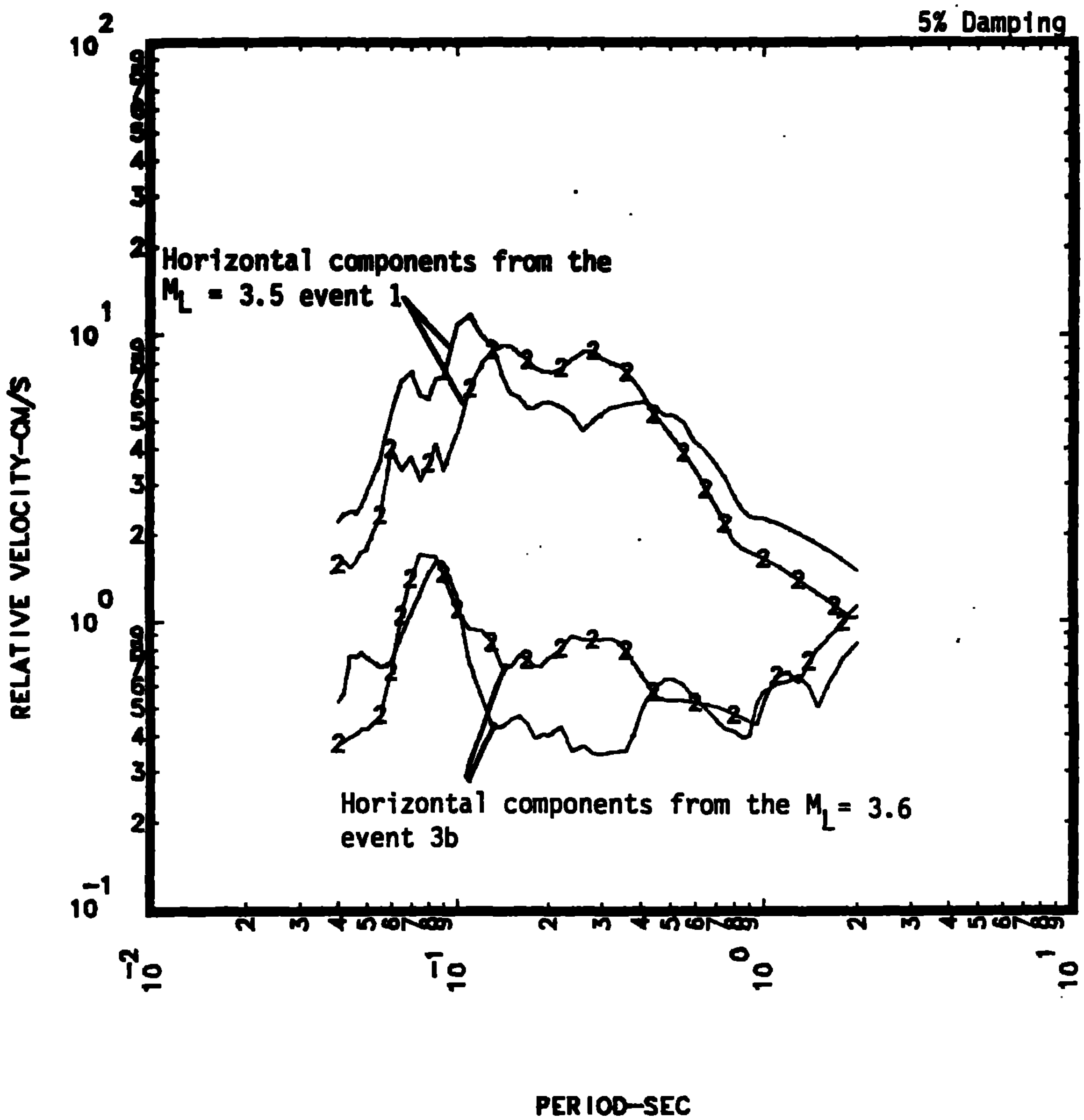

Fig. 5.2 Comparison of the spectra from two earthquakes located within a few kilometers of each other with similar magnitudes and recorded at the Brawley Airport. Event numbers and magnitudes from Johnson and Hanks (1976).

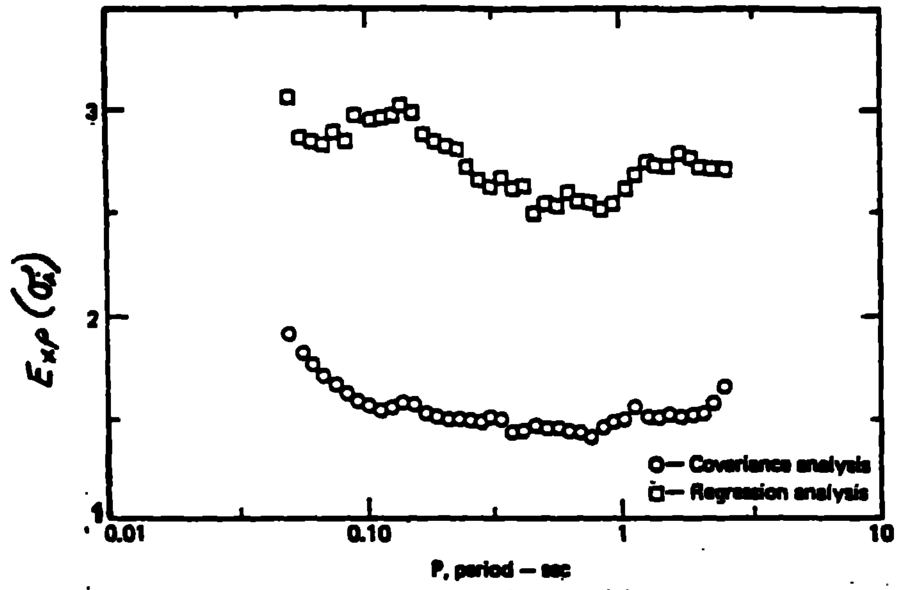

Fig. 6.1 Comparison of Exp (σi) obtained from a covariance analysis accounting for each site to that obtained by Lynch (1969) which does not include site factors.

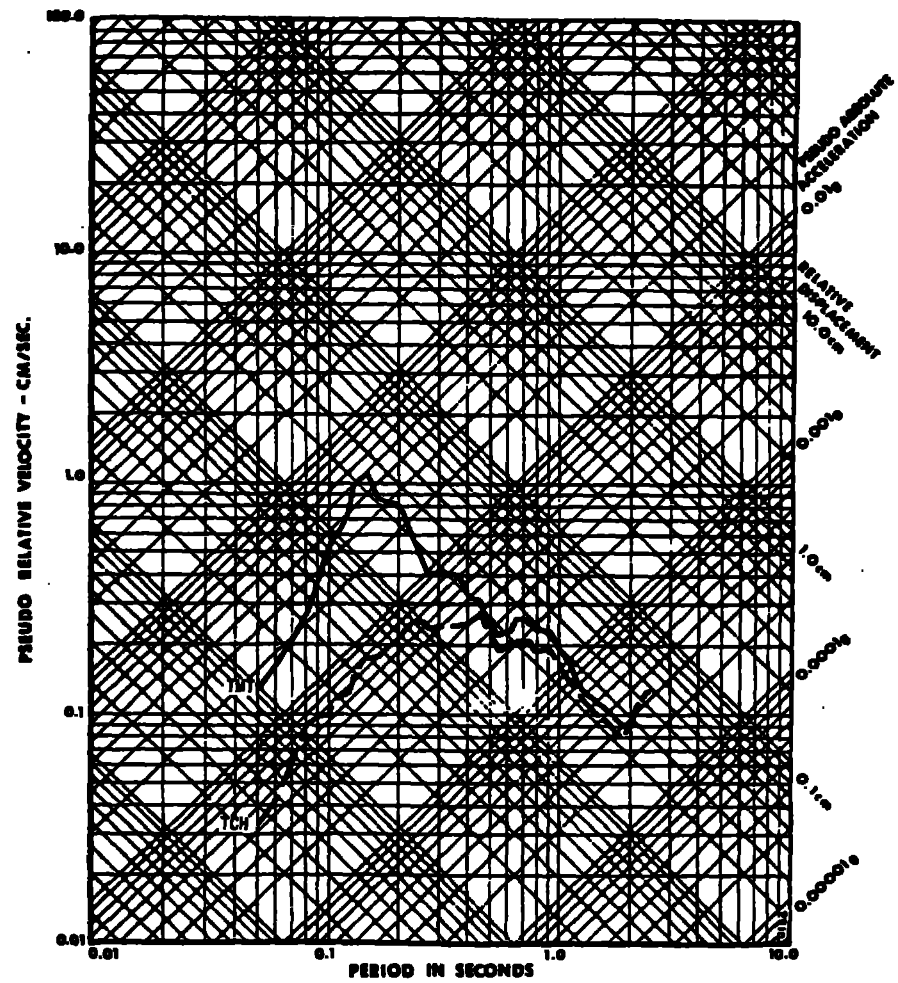

Fig. 6.2 Comparison of the radial component of the spectra from two nearby stations TMT (Tonopha motel, shallow alluvium) and TCH (Tonopah church, rock).

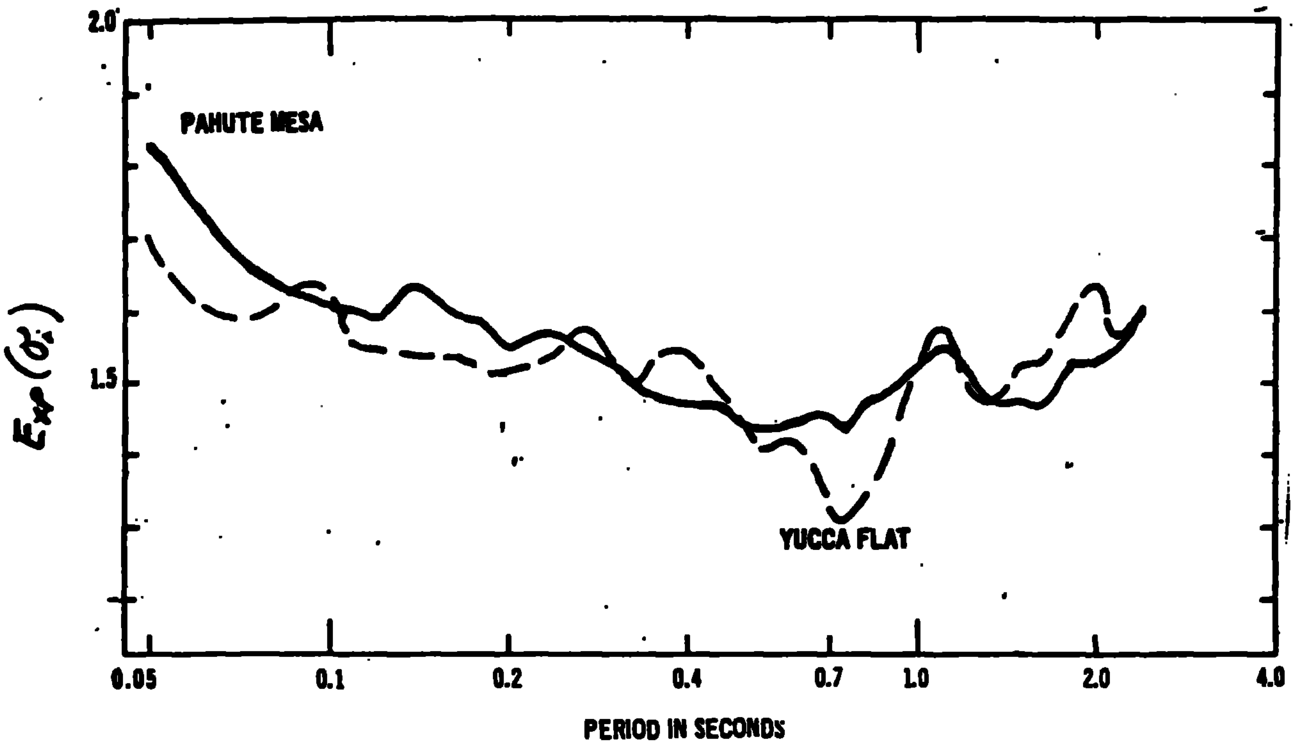

Fig. 6.3 Comparison of Exp (σ_i) for the covariance analysis for Pahute Mesa UNE (Fig. 6.1) to that for Yucca Flat UNE.

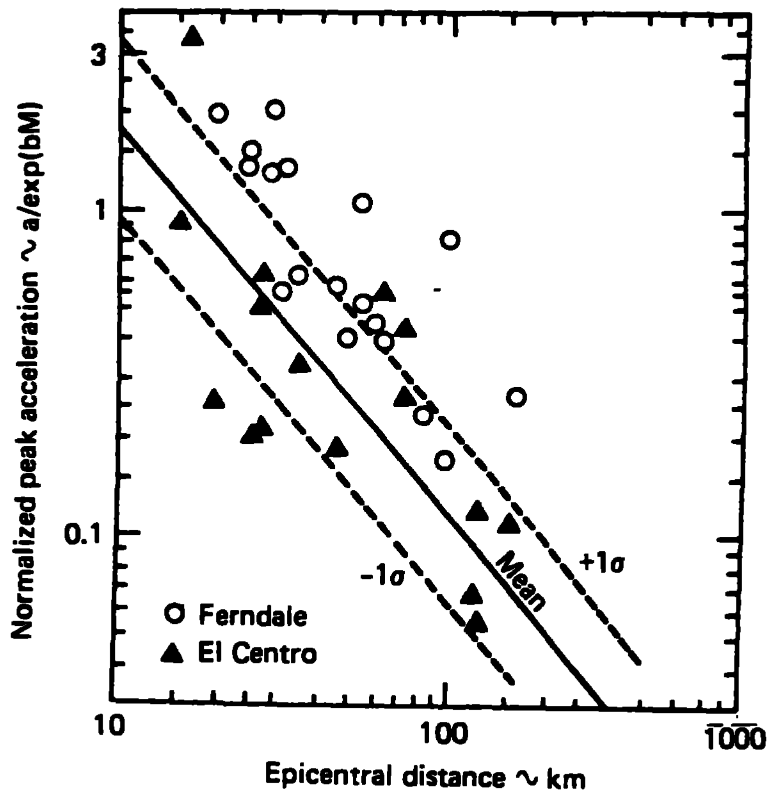

Fig. 6.4 Normalized peak accelerations recorded at El Centro and Frendale sites compared with McGuire's (1978) correlation.

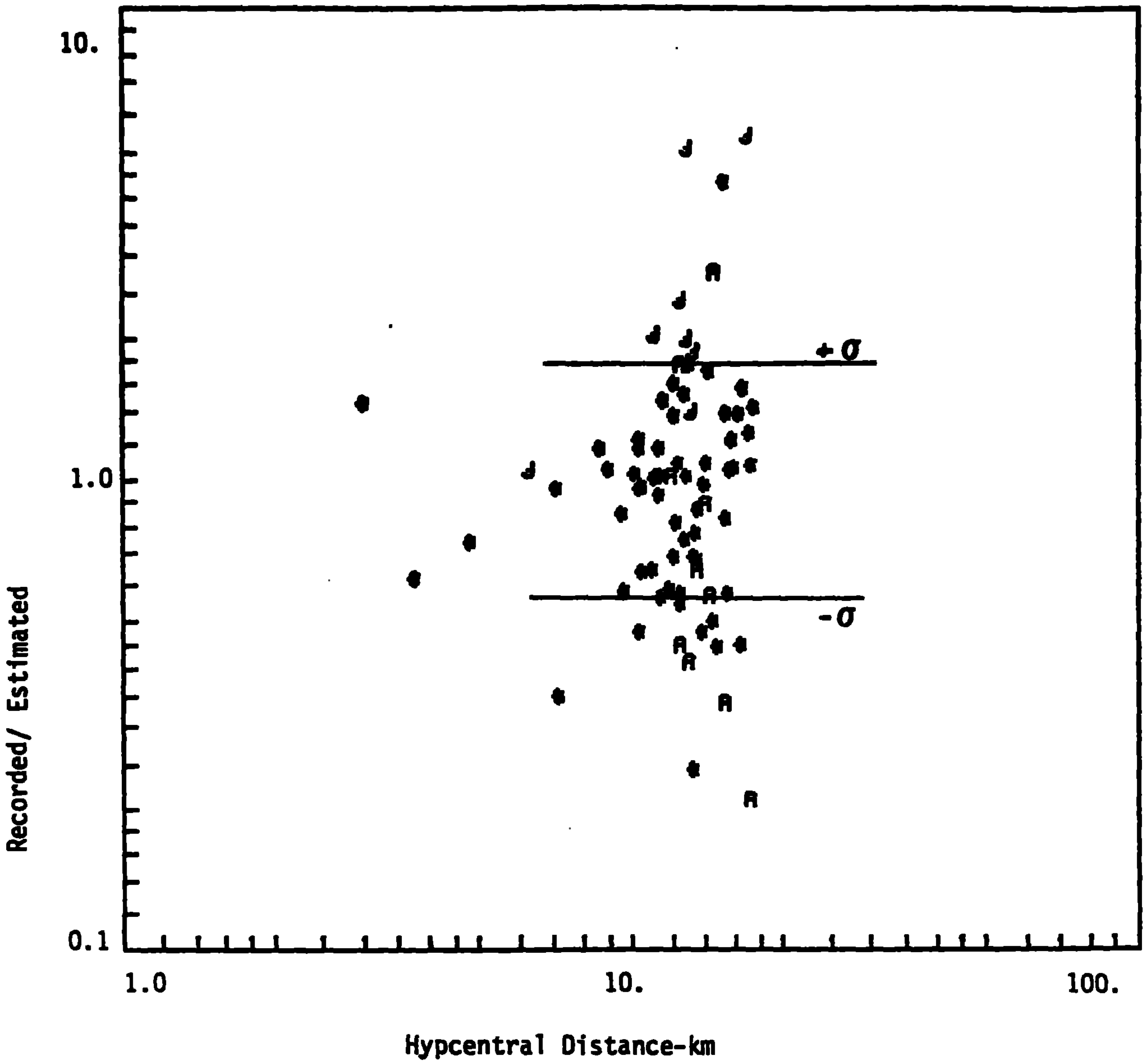

Fig. 6.5 Normalized peak horizontal acceleration for the Oroville data set. The data for Johnson Ranch are denoted by J and for the Oroville Airport by A. The data from the other stations are denoted by *.

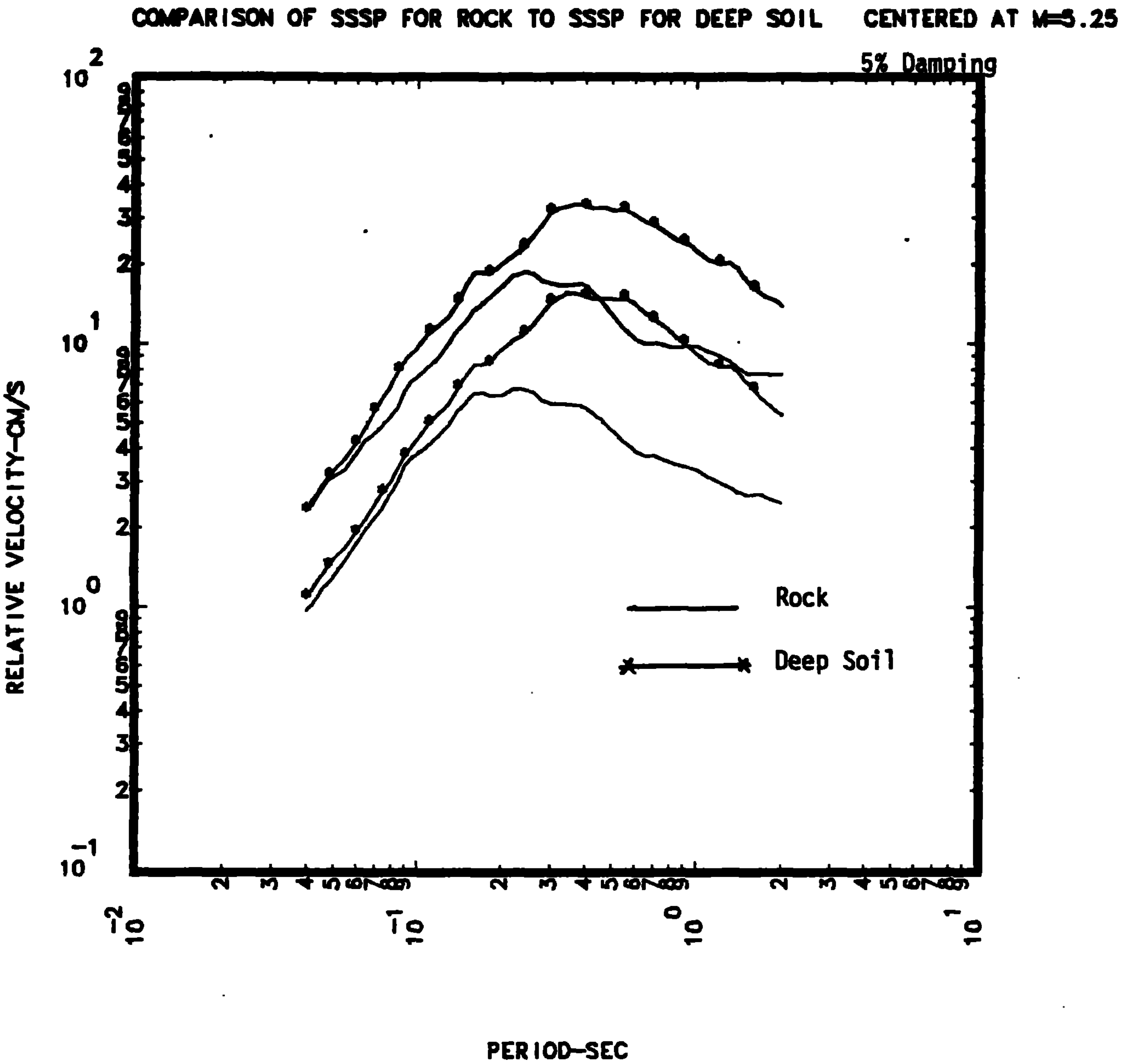

Fig. 8.1a Median and 84 th percentile SSSP for rock and deep soil sites for a SSE of MMVII

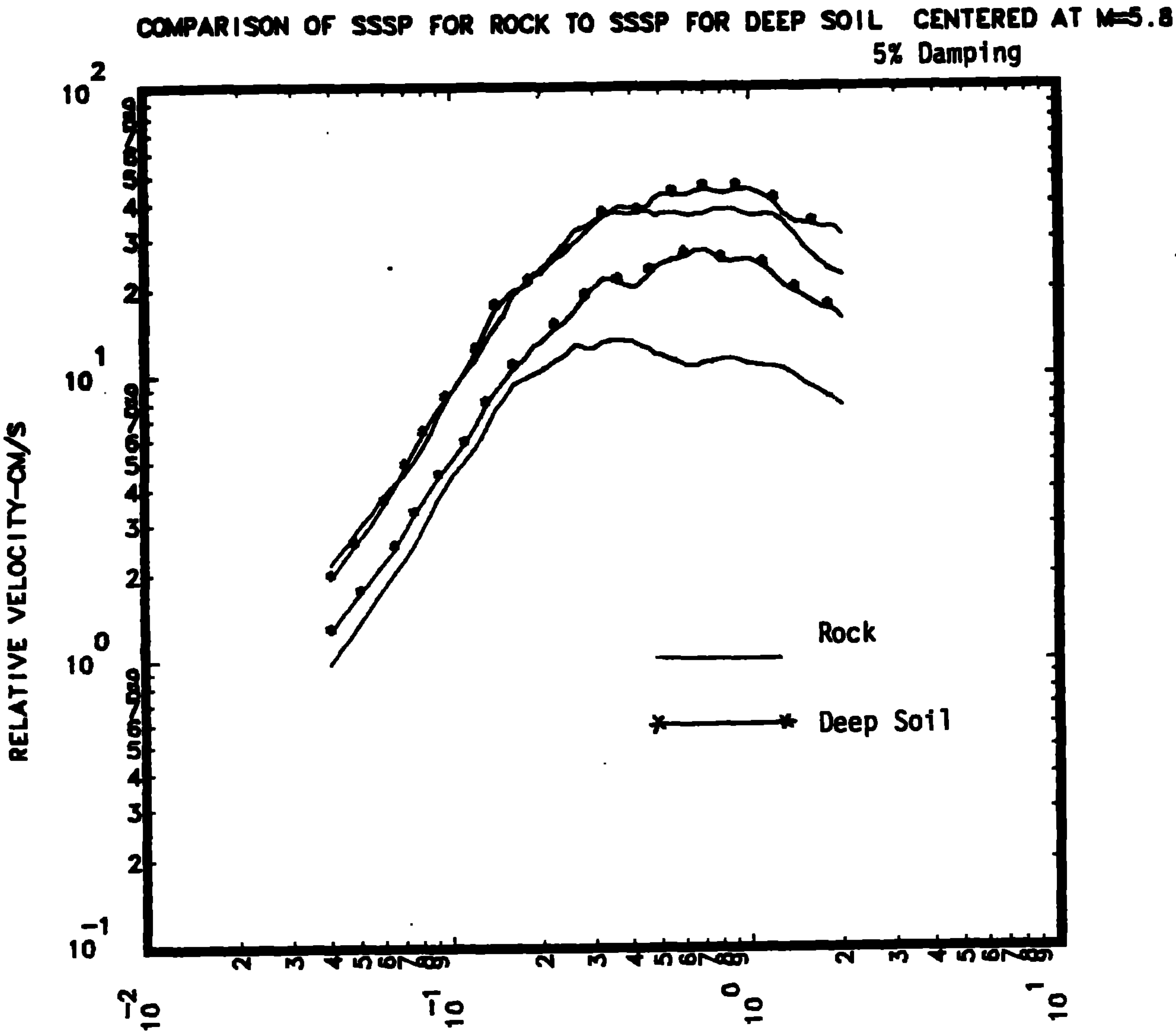

Fig. 8.1b Median and 84th percentile spectra for rock and deep soil sites for a SSE of MMVIII.

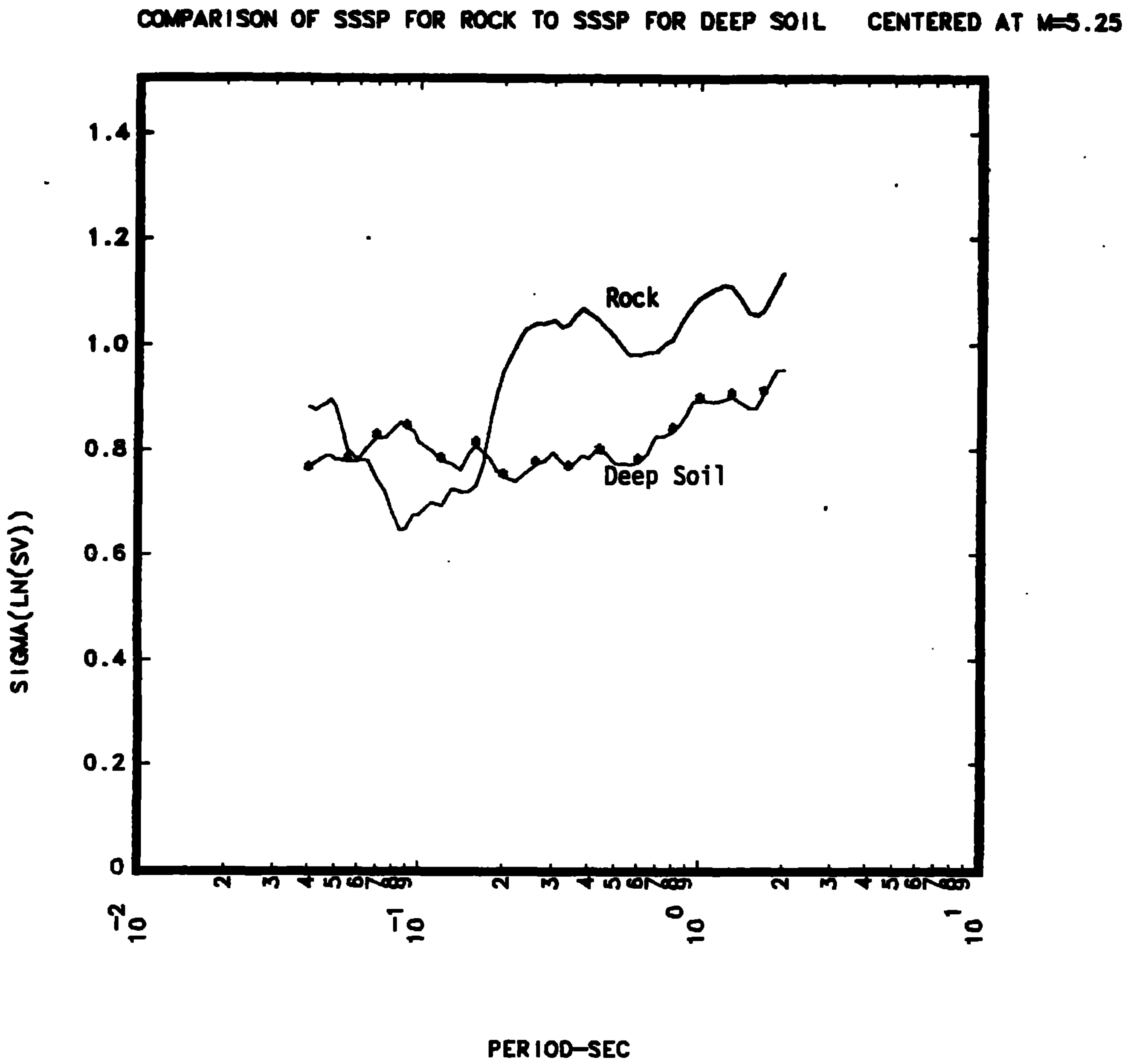

Fig. 8.2 Uncertainty of the estimated SSSP for rock and deep soil sites for a SSE of MMVII as measured by the standard deviation of the assumed lognormal distribution of the spectral velocity S_v.

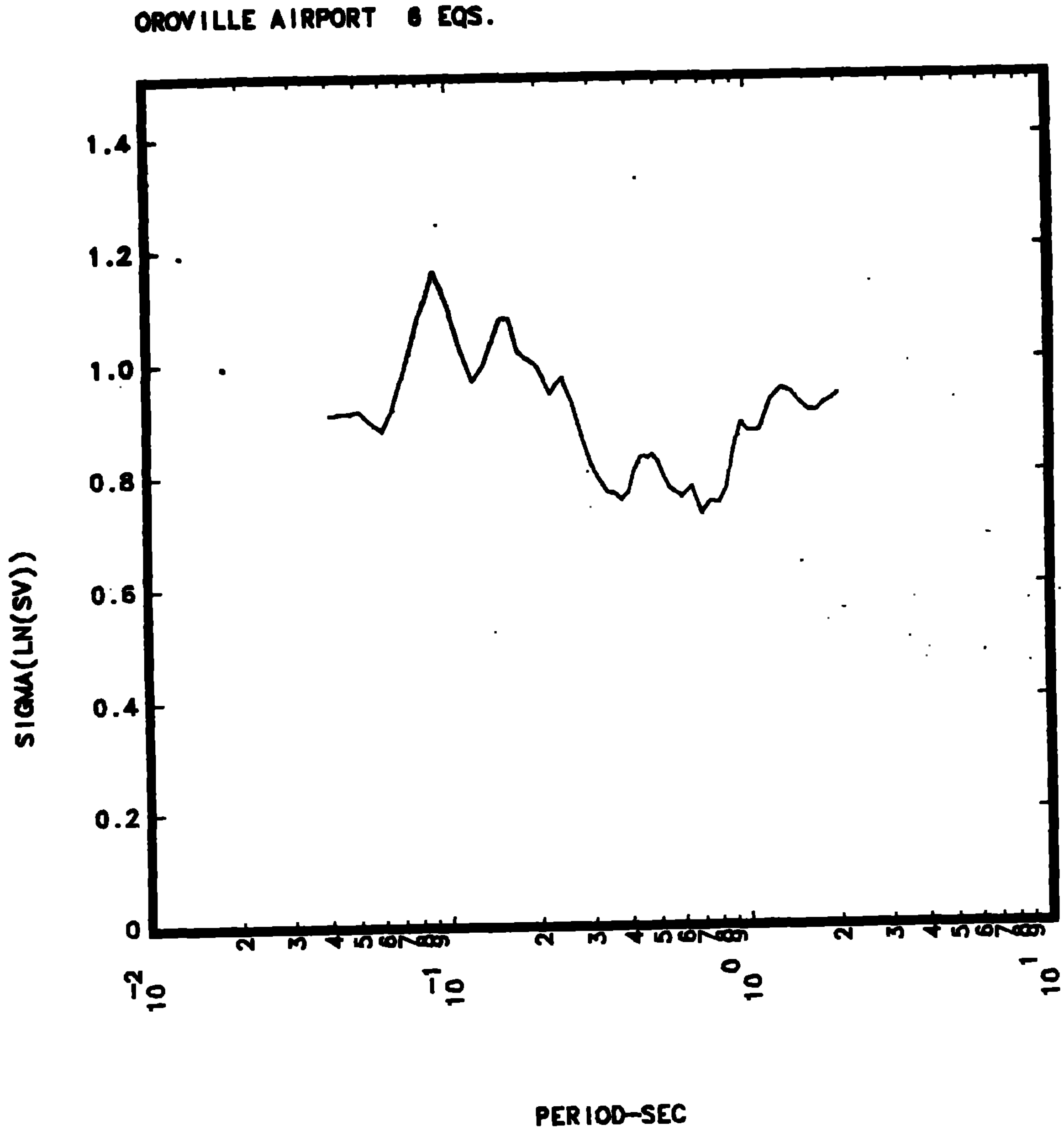

Fig. 8.3 Uncertainty of a SSSP for the Oroville Airport based on six earthquakes of $M_L = 4.7 \pm 0.5$ units recorded at the Oroville Airport as measured by the standard deviation of the assumped lognormal distribution of the spectral velocity.

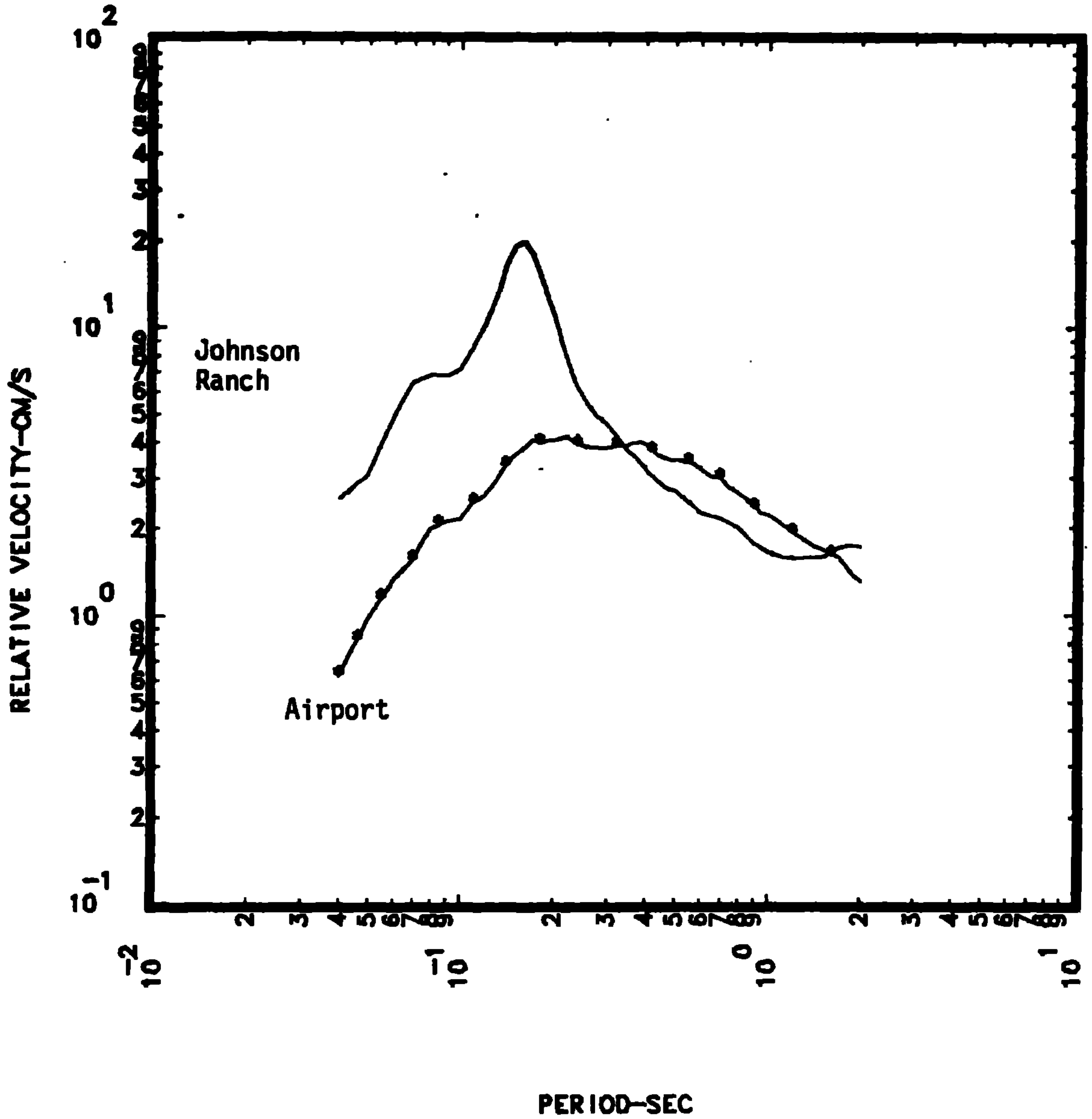

Fig. 8.4 Difference in spectral shape between a deep soil site (Oroville Airport) and a shallow soil (Johnson Ranch) using only data recorded at the respective sites. Note that only two events are common to both sites.